Technicolor

Status and Prospects

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March 4, 1998
ANL

OUTLINE

- Motivation for Strong Dynamics
- Overview of Technicolor and variants
- Technicolor Signatures
- Technicolor Production at hadron colliders
  - Searches at CDF
- Technicolor Production at $\mu^+\mu^-$ colliders
- Summary

NEW STRONG DYNAMICS

- Success of the Standard Model has been spectacular!
- But, new physics seems inevitable!
  - the cause for electroweak symmetry breaking and the origin of fermion masses and mixings are unknown
- There are two enticing theoretical approaches to understand EWSB
  - Supersymmetry
    (Elementary scalar bosons)
  - Strong Dynamics
    (composites bound by a new strong interaction)

OVERVIEW OF TECHNICOLOR

- Weinberg, Susskind 1979
- Technicolor (TC) is a strong interaction of new fermions (technifermions) and gauge bosons at a scale of $\Lambda_{TC} \sim 1$ TeV
- causes dynamical breaking of electroweak symmetry
  - No Higgs! No elementary scalar bosons
- Inspired by QCD precedent
  - QCD breaks chiral symmetry of massless quarks, leads to pseudo-Goldstone bosons π, k, η, ...
  - Would break $SU(2) \times U(1)$ in the absence of Higgs
  - Gives mass to W and Z with correct m_W/m_Z, but $m_W^2 = \frac{1}{8} g^2 N_f f_\pi^2$

$f_\pi = 93$ MeV

$m_W \sim 50$ MeV

TECHNICOLOR (contd.)

- TC as scaled up QCD to the TeV scale
  - new technifermions as SU(2) doublet and singlets
  - $m_W = m_Z \cos\theta_W = \frac{1}{2} g F_\pi$

    $F_\pi = 246$ GeV
  - $3\ \pi_T^{\pm,0} \Rightarrow W_L^\pm, Z_L^0$
- $N_D > 1$ technidoublets

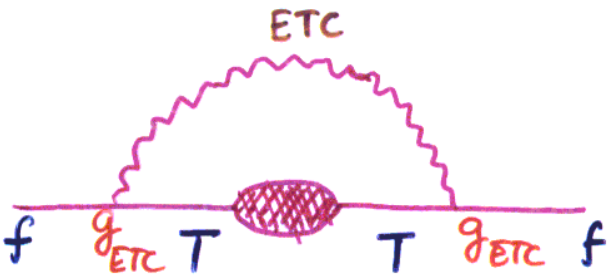
  $\Rightarrow N_D - 4$ extra π_T

How do they get mass ?

How do the SM fermions get mass?

EXTENDED TECHNICOLOR

- Dimopoulos & Susskind ; Eichten & Lane, 1979
- TC does not provide for "hard masses." The SM fermions can acquire masses if they couple to technifermions via additional gauge interactions (ETC)



$$m_f \simeq \frac{g_{ETC}^2}{M_{ETC}^2} \langle T\bar{T} \rangle_{ETC}$$

- Break $G_{ETC} \to G_{TC} \otimes G_{QCD} \otimes G_F$ at some high energy scale, $\Lambda_{ETC} = \mathcal{O}(100\,TeV)$

So,

In the standard Higgs model of EWSB,

→ the Higgs potential breaks $SU(2) \times U(1)$

→ $v \neq 0$ endows $W^{\pm}$, Z with masses

→ Quarks and leptons get masses through arbitrary Yukawa couplings to the Higgs field

In the technicolor scenario,

→ TC interactions become strong at low energies, forms a technifermion condensate that breaks chiral symmetry

→ Gives mass to $W^{\pm}$, Z

→ New ETC gauge bosons couple fermions to technifermions, allowing the fermions to communicate with the condensate and acquire mass

BUT, TOP QUARK IS HEAVY!

- $m_t = 175.6 \pm 5.5$ GeV/c^2 (CDF+DØ)
- "Top quark is a remarkable particle, even for a quark." – Quigg
- Heaviest fundamental particle known
- Top quark is <u>the</u> elementary particle most strongly coupled to the mechanism of mass generation and/or to the dynamics of EWSB $\left(G_t = \frac{m_t \sqrt{2}}{v}\right)$

Top quark may have

unique dynamics !!!

Another major turning point:

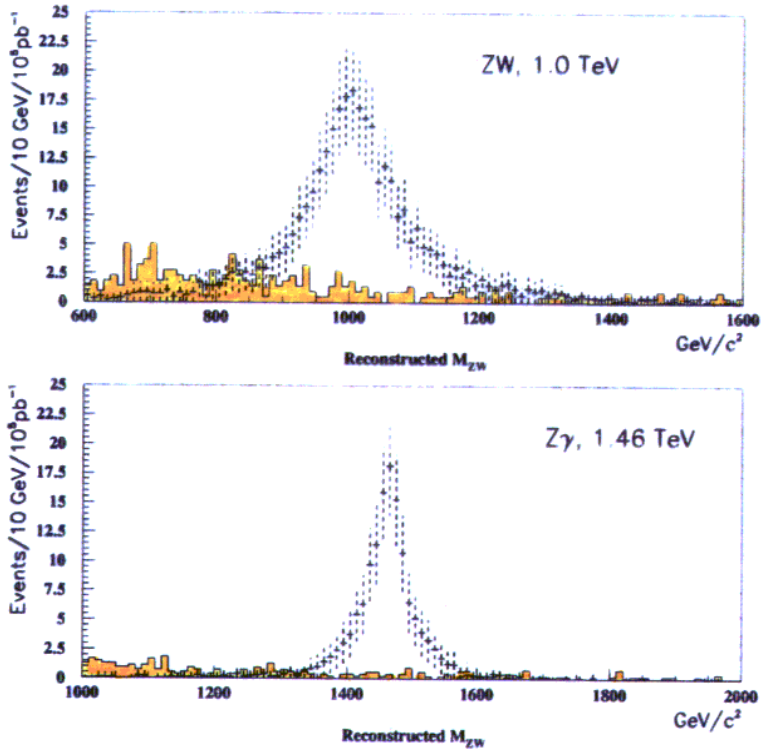
→ Topcolor-assisted technicolor

C. Hill, Phys. Lett. B 345 (1995) 483

CLASSICAL TECHNICOLOR

Models

- **Minimal one-doublet**
  - *technifermions are (U,D)*
  - *only low-lying state is $\rho_T \sim 1.5 - 2$ TeV, s-channel resonance in WW,WZ production [see e.g. EHLQ, 1984; ATLAS TP]*



$\rho_T \rightarrow WZ$

SM

$\omega_T \rightarrow Z\gamma$

TECHNICOLOR SIGNATURES
(Non-minimal)

- The lightest new particles are technipions ($\gtrsim 100$ GeV)

$$\pi_T^0 \longrightarrow t\bar{t},\ b\bar{b},\ c\bar{c},\ \tau^+\tau^-$$
$$\pi_T^{0\prime} \longrightarrow gg,\ t\bar{t},\ b\bar{b},\ \ldots$$
$$\pi_T^+ \longrightarrow c\bar{b},\ c\bar{s},\ \tau^+\nu_\tau$$

- Color-singlet technirhos ($m \sim 200$–400 GeV)

$$\rho_T^\pm \longrightarrow W^\pm Z,\ \underline{W^\pm \pi_T^0},\ Z\pi_T^\pm,\ \pi_T^\pm \pi_T^0$$
$$\rho_T^0 \longrightarrow WW,\ \underline{W\pi_T},\ \pi_T\pi_T$$

- Color-octet technirhos ($m \sim 200$–600 GeV)

$$\rho_{T8} \longrightarrow \pi_T\pi_T,\ gg \qquad (\pi_T\pi_T \longrightarrow 4 \text{ jets } (b\bar{b}\,b\bar{b}))$$

1–10 pb Tevatron
1–10 nb LHC

- Color-singlet techniomega

$$\omega_T \longrightarrow \underline{\gamma\pi_T^0},\ Z\pi_T^0,\ q\bar{q},\ \ell^+\ell^-$$

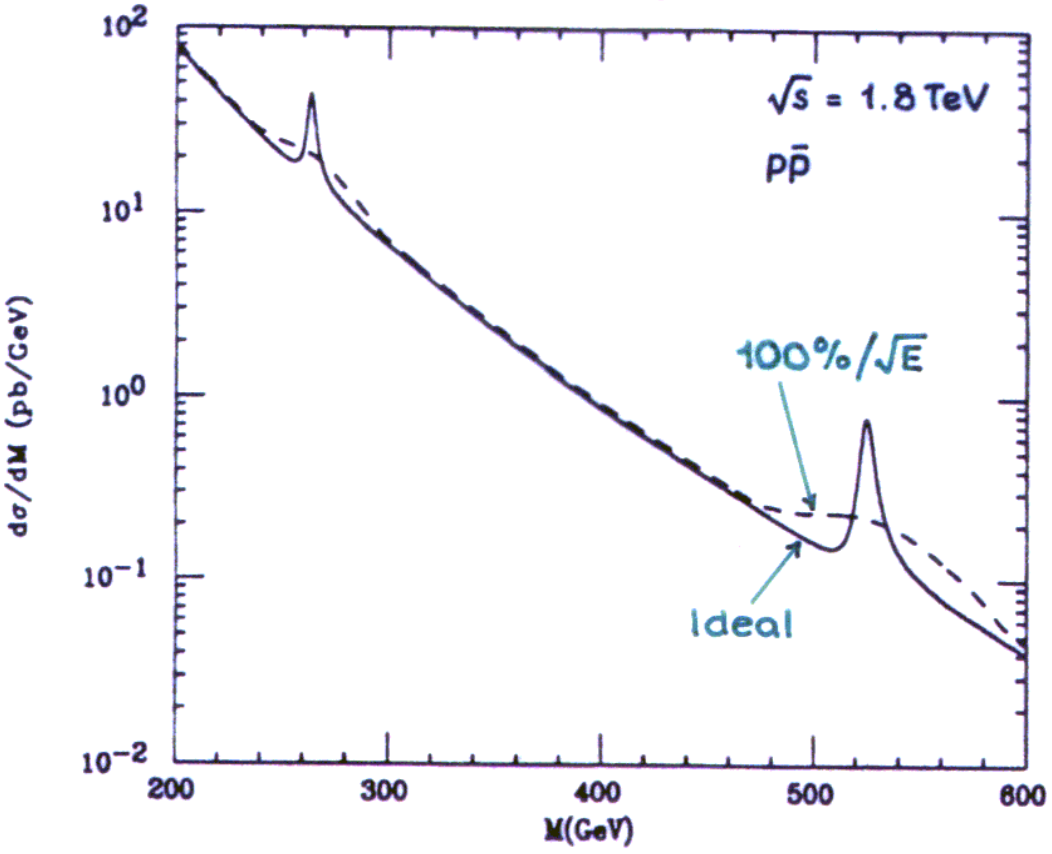
Eichten & Lane
Snowmass 1996

Process	Sample Mass (GeV)	$\sigma_{\rm TeV}$(pb)	$\sigma_{\rm LHC}$(pb)
$\rho_{T1} \to W_L \pi_T$ [1]	220(ρ_{T1}), 100(π_T)	5	35
$\rho_{T1} \to \pi_T \pi_T$ [1]	220(ρ_{T1}), 100(π_T)	5	25
$gg \to \pi_T^0 \to b\bar{b}$ [2]	100	300/5000	7000/10^5
$gg \to \eta_T \to t\bar{t}$ [3]	400	3/3	2000/600
$gg \to \pi_T \pi_T$ [4]	100	0.2	600
$\rho_{T8} \to$ jet jet [5]	250(ρ_{T8})	700/5000	1.5×10^4/1.5×10^5
	500(ρ_{T8})	10/40	2000/6000
$\rho_{T8} \to \pi_{T8} \pi_{T8}$ [6]	550(ρ_{T8}), 250(π_{T8})	2	2000
$\rho_{T8} \to \pi_{Q\bar{L}} \pi_{L\bar{Q}}$ [6]	550(ρ_{T8}), 200($\pi_{Q\bar{L}}$)	2	1000
$V_8 \to t\bar{t}$ [7]	500	8/3	100/600
Λ reach [8]	5 TeV (TeV), 20 TeV (LHC)	10 fb^{-1}	100 fb^{-1}

Table 1. Sample cross sections for technicolor signatures at the Tevatron and LHC.

Signal over background rates shown as S/B

$p_{T8} \rightarrow q\bar{q}, gg \rightarrow$ jets

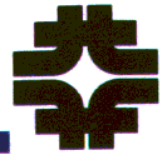


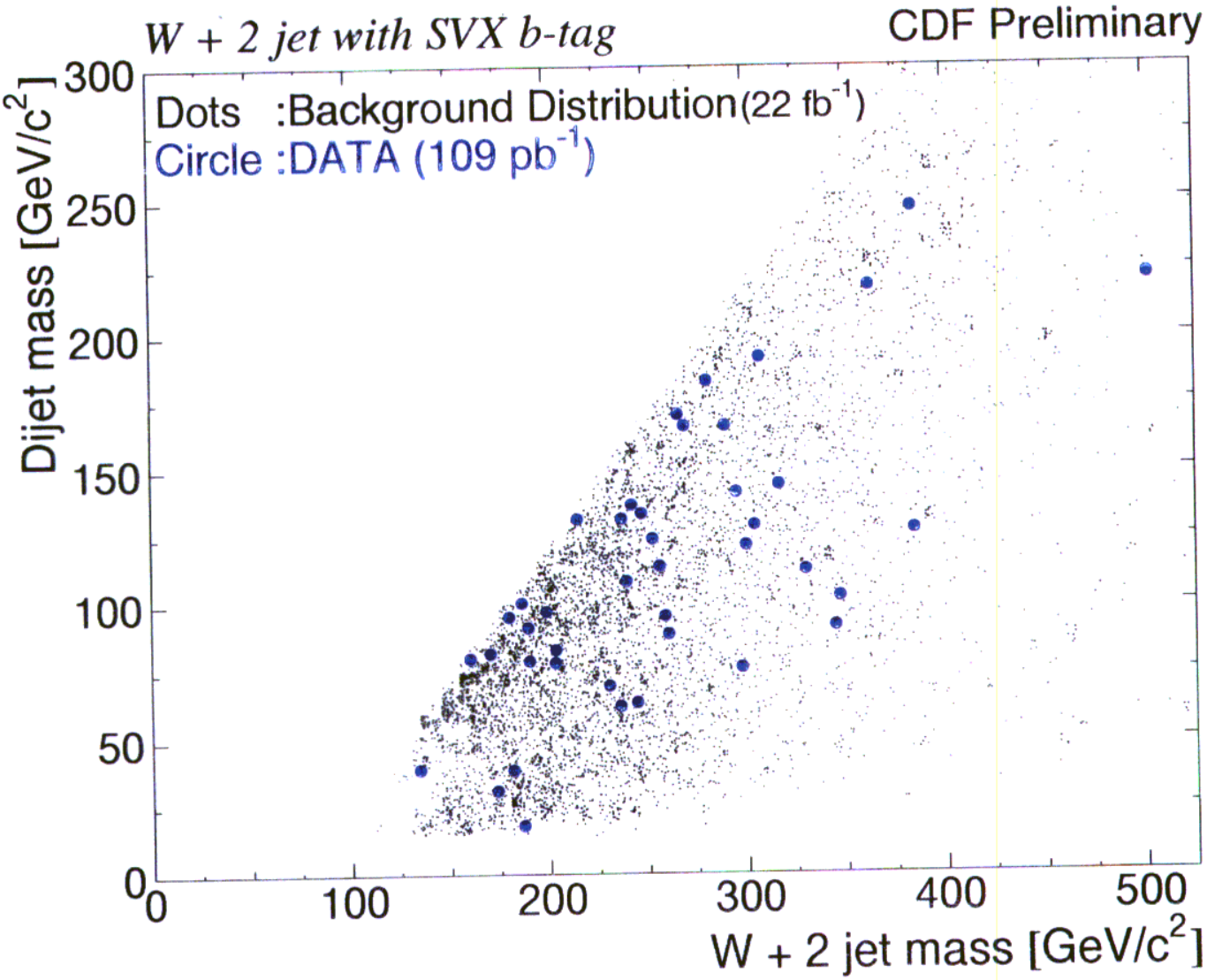
Mass reach ~ 800-900 GeV with 2 fb^{-1}

Techniomega production

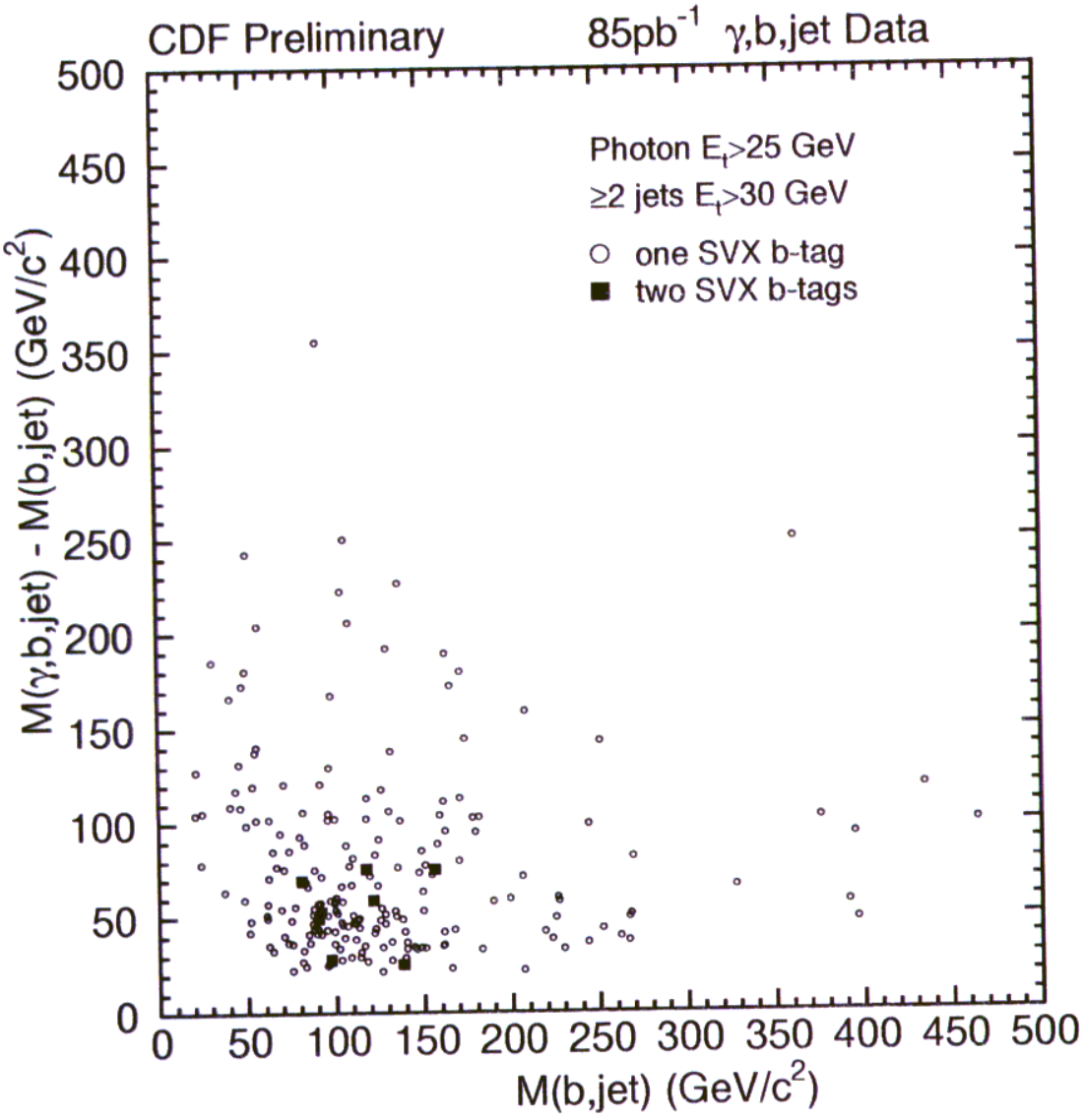
$$qq' \rightarrow Z^* \rightarrow \omega_T \rightarrow \gamma\pi_T$$

- Signal is photon + 2 *b*-jets: $\sigma \cdot B = 2.6$ pb
- Dominant background is γ+jets: $\sigma \cdot B = 740$ pb ($p_T^{\gamma} > 45$ GeV)
- Require a high p_T photon
  - $p_T > 50$ GeV/c, $|\eta| < 1.1$
- Require two jets
  - $E_T > 20$ GeV, $|\eta| < 2.0$, $\Delta R > 0.7$ from γ
- Topological cuts
  - $\Delta\phi^{jj} > 90°$
- *b*-tagging as before



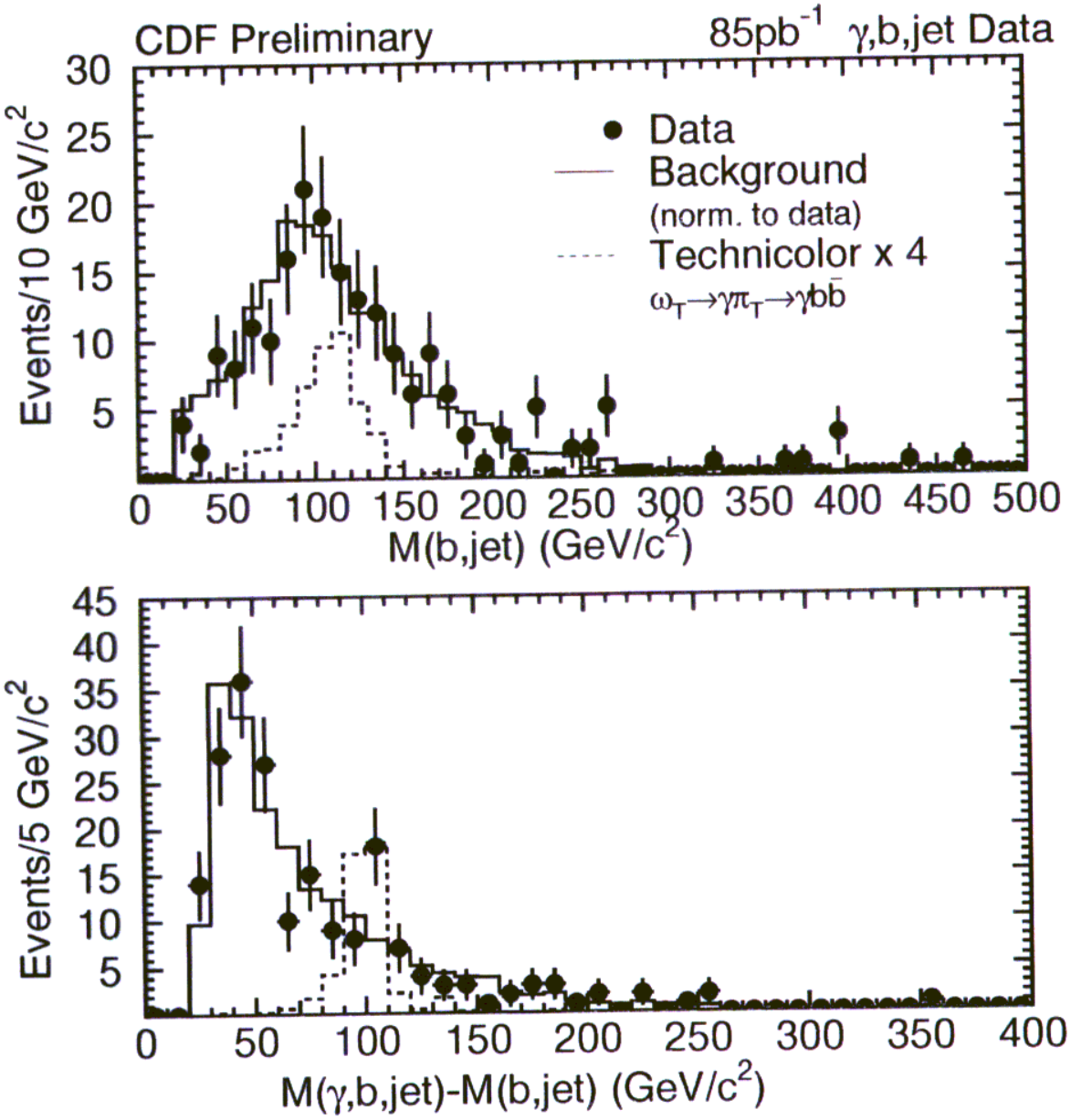

W + 2 jet with SVX b-tag
CDF Preliminary
Dots :Background Distribution(22 fb-1)
Circle :DATA (109 pb-1)
Dijet mass [GeV/c2]
W + 2 jet mass [GeV/c2]
0
50
100
150
200
250
300
0
100
200
300
400
500

→ 200 events observed, 131±30±29 expected:

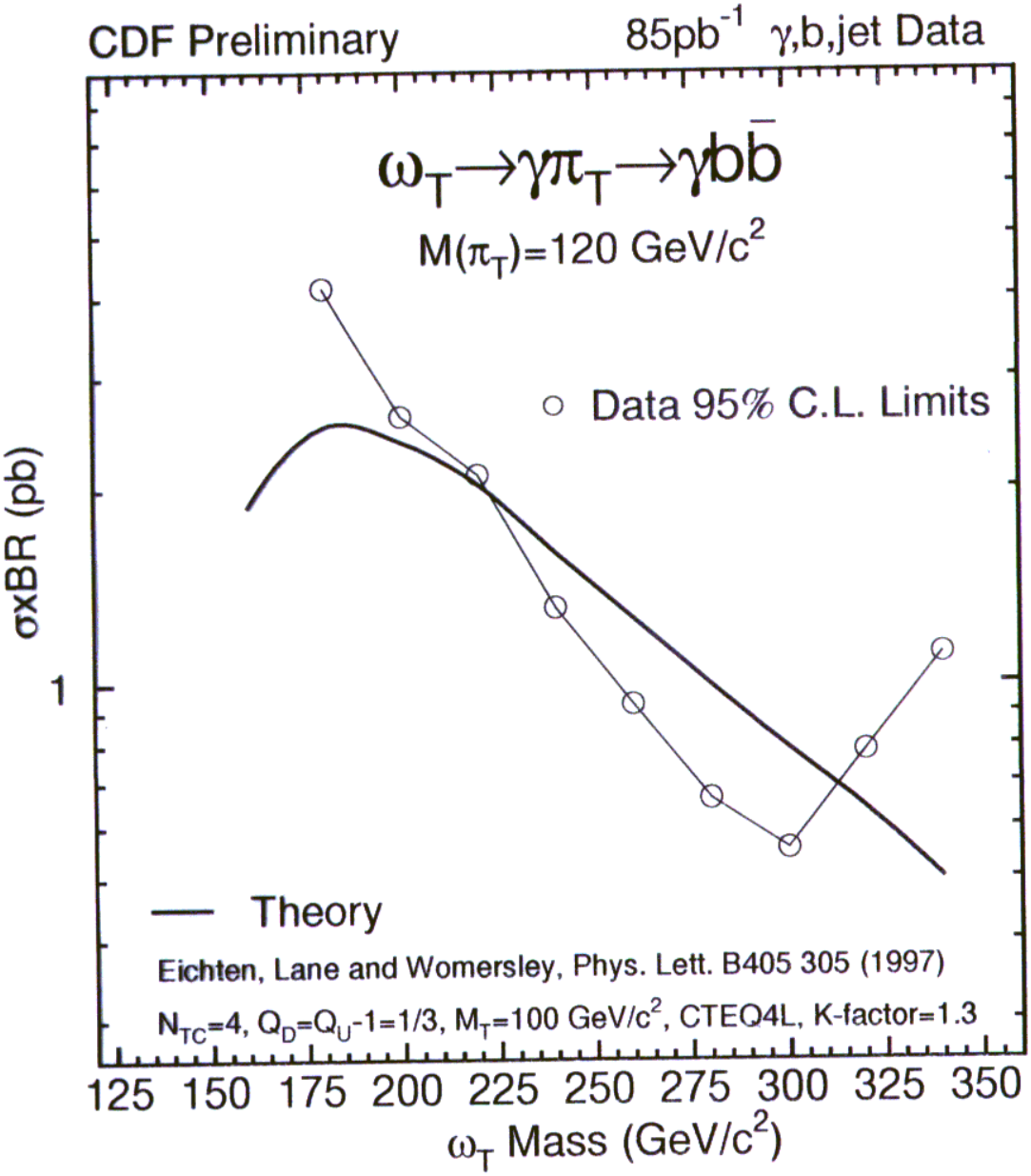


→ signal would be "spot" on plane

projections of previous plot:



cross section limits for particular mass choice:



TOPCOLOR SIGNATURES

- All the previous technicolor signatures plus:
- Isotriplet of "top-pions" π_t from breakdown of $SU(3) \times U(1)$

  $\pi_t \to t\bar{b}$ or $t \to \pi_t b$
- "Top-rho" ρ_t $(m \sim 2m_t - 1\ \text{TeV})$

  $\rho_t \to \pi_t \pi_t$, $t\bar{t}$, $b\bar{b}$
- Color-octet gauge bosons – colorons or topgluons $(m \sim 0.5 - 2\ \text{TeV}, \Gamma/m \sim 0.5)$
  - resonances in $b\bar{b}$, $t\bar{t}$ production
  - $\sigma \sim 1-10$ pb (Tevatron), 100 pb – 1 nb (LHC

  $V_8/B \longrightarrow b\bar{b}, t\bar{t}$
- Topcolor Z'

  $Z_t' \to t\bar{t}$

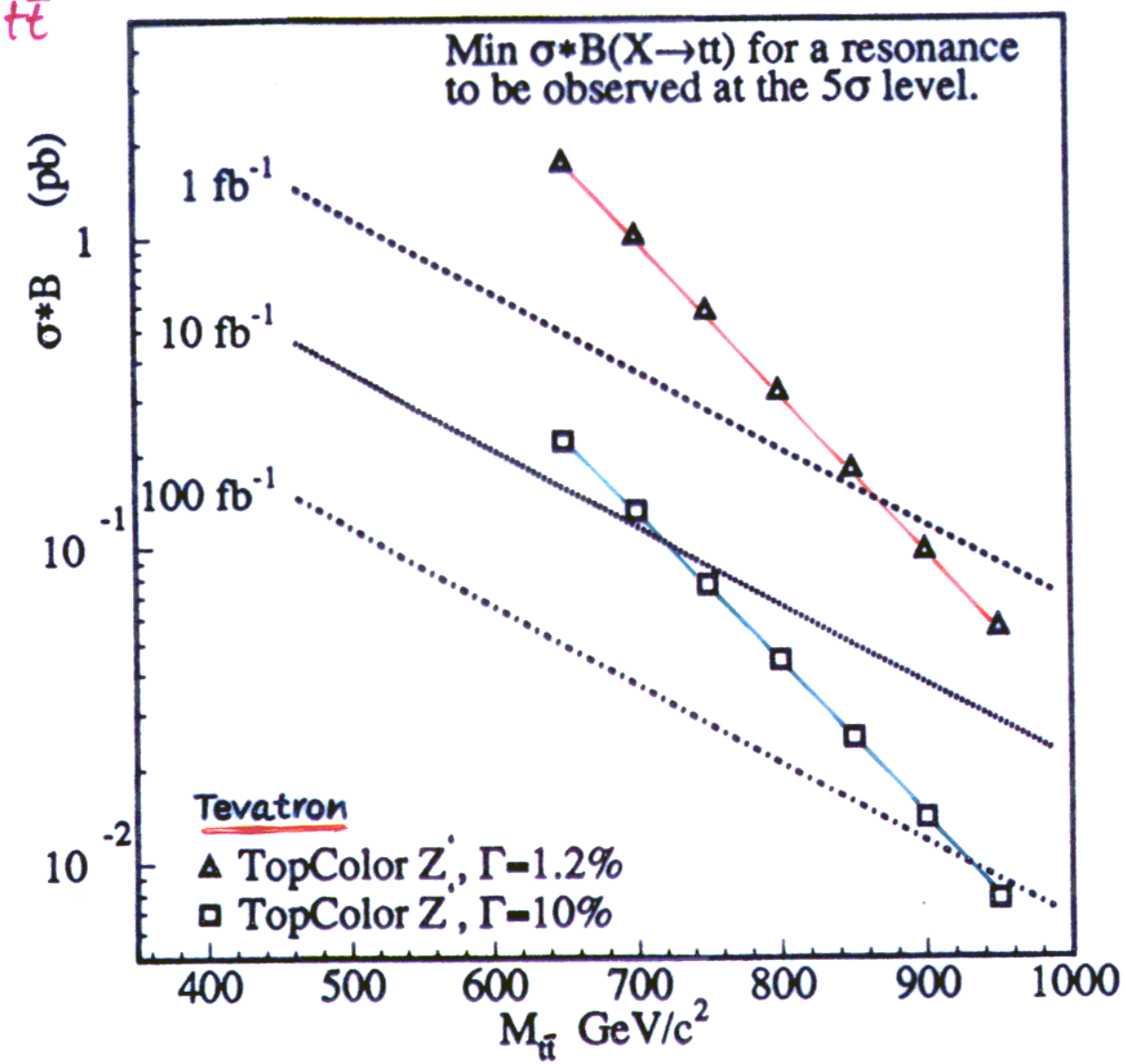
K. Tollefson

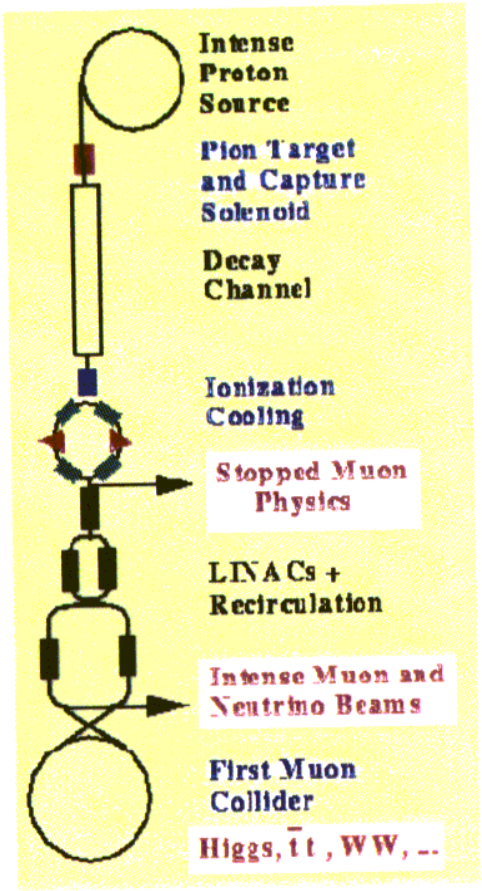
Topcolor Z' associated with breakdown of $U(1)_3$

mass ~1-3 TeV

$Z' \rightarrow t\bar{t}$

Resonance in $t\bar{t}$





Workshop on Physics at the First Muon Collider and at the Front End of a Muon Collider

Thursday-Sunday, November 6-9,1997

Fermi National Accelerator Laboratory

Batavia, Illinois USA

A large ongoing effort is being devoted to assessing the feasibilty of building a high-energy muon collider. Initial results from the machine design studies are encouraging. The First Muon Collider (FMC) is envisaged as a machine producing $\mu^+\mu^-$ collisions at a center-of-mass energy in the range from m_Z up to above the t tbar threshold. This would provide a step towards a very high energy collider (a 4 TeV muon collider, for example). In addition to the collider ring, the FMC requires a very intense muon source that provides a variety of additional physics possibilities. The FMC accelerator complex would evolve within the following parameter ranges:

- An intense low energy proton source delivering initially 6×10^{20} protons/year and ultimately 1.5×10^{22} protons/year at 8 GeV/c or above.
- An extremely intense very low energy muon source producing, for example, initially 8×10^{19} muons/year, and ultimately 2×10^{21} muons/year at ~100 MeV/c.
- A muon accelerator complex producing muon beams with energies up to a maximum of, for example, 200 GeV, and the accompanying neutrino beams.

TECHNICOLOR AT THE MUON COLLIDER

- The low energy technihadrons can be probed at the FMC with $\sqrt{s} = 100\text{-}500$ GeV
- Specifically, neutral technipions and technivectors are very narrow and can be produced as s-channel resonances
- Coupling to $\mu^+\mu^- \sim m_\mu / v$ $\quad v \simeq 246$ GeV

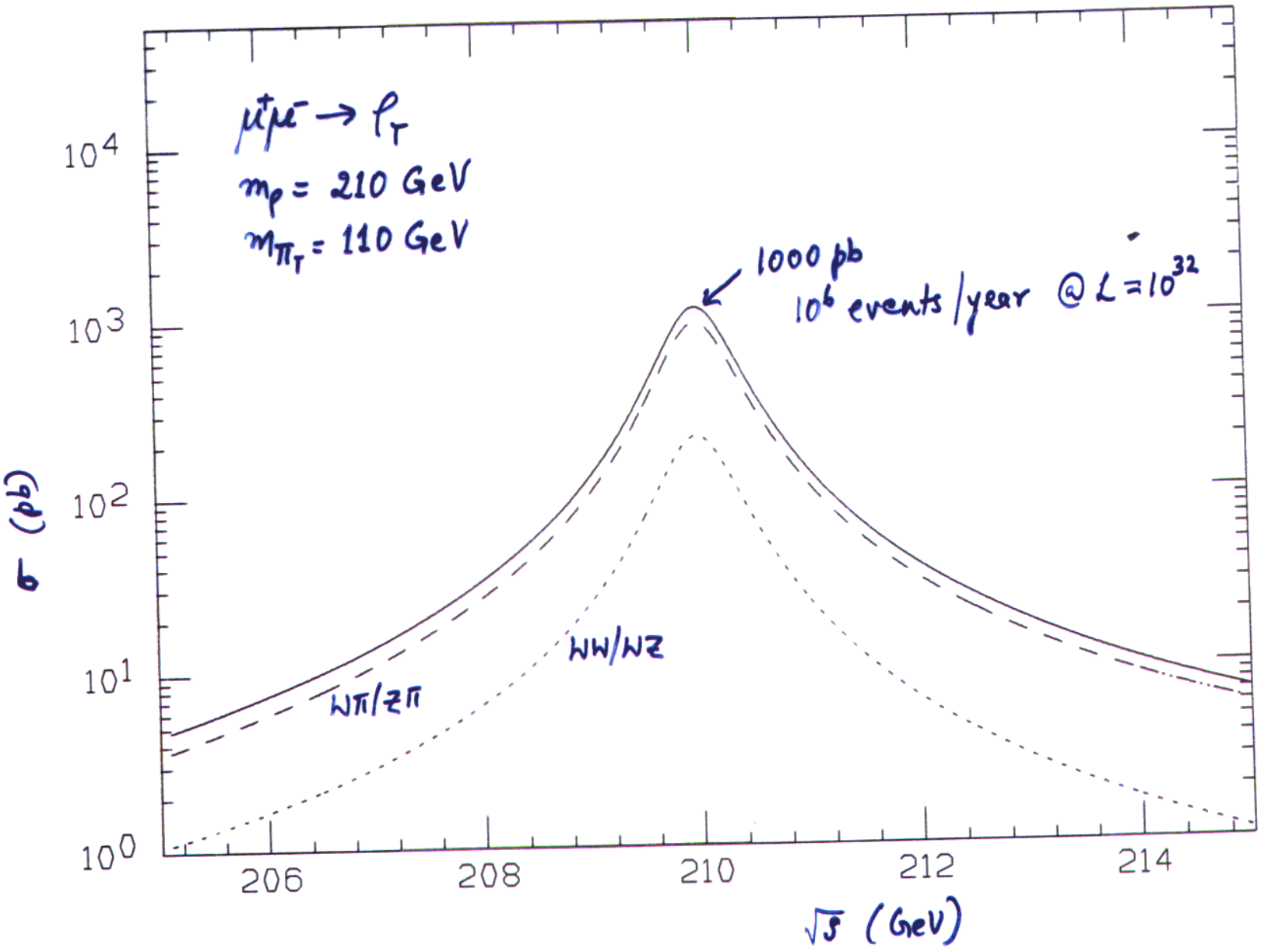
  So, $\sigma \propto m_\mu^2$

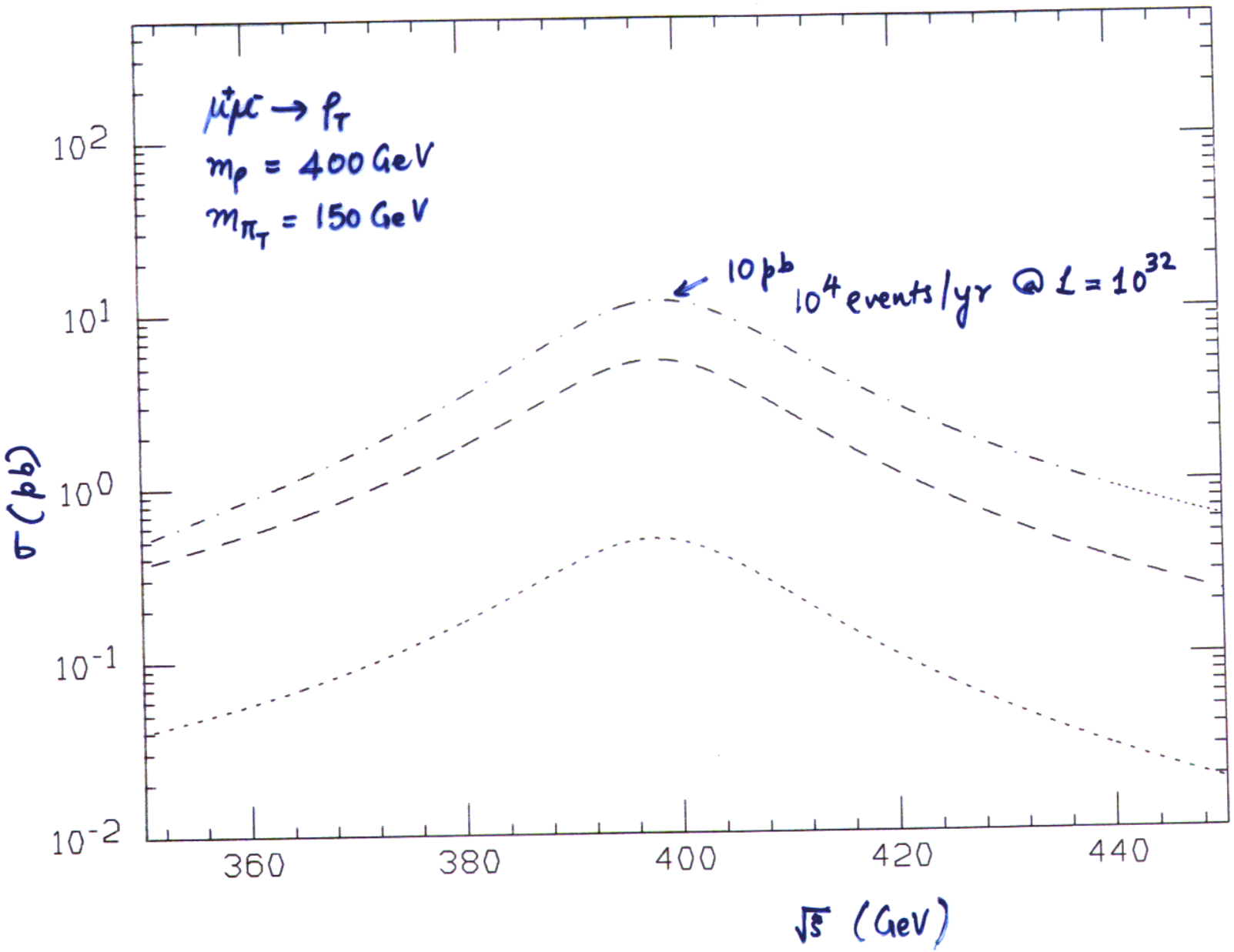
  $= 10^4$ times better than at e^+e^-

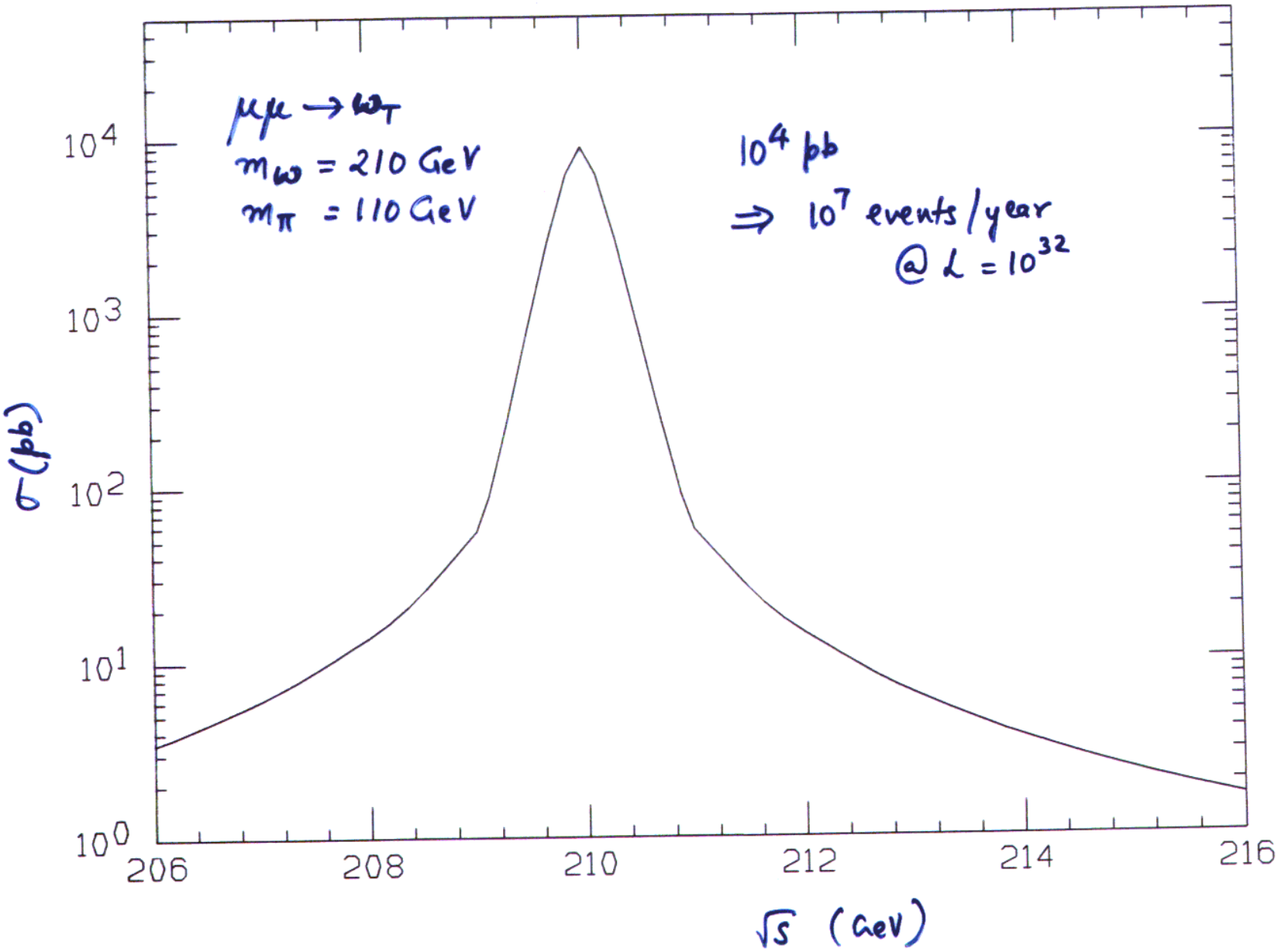
  $\sim 0.1 - 10$ nb

Also, $\delta p/p \sim 10^{-3}$ to 10^{-5}

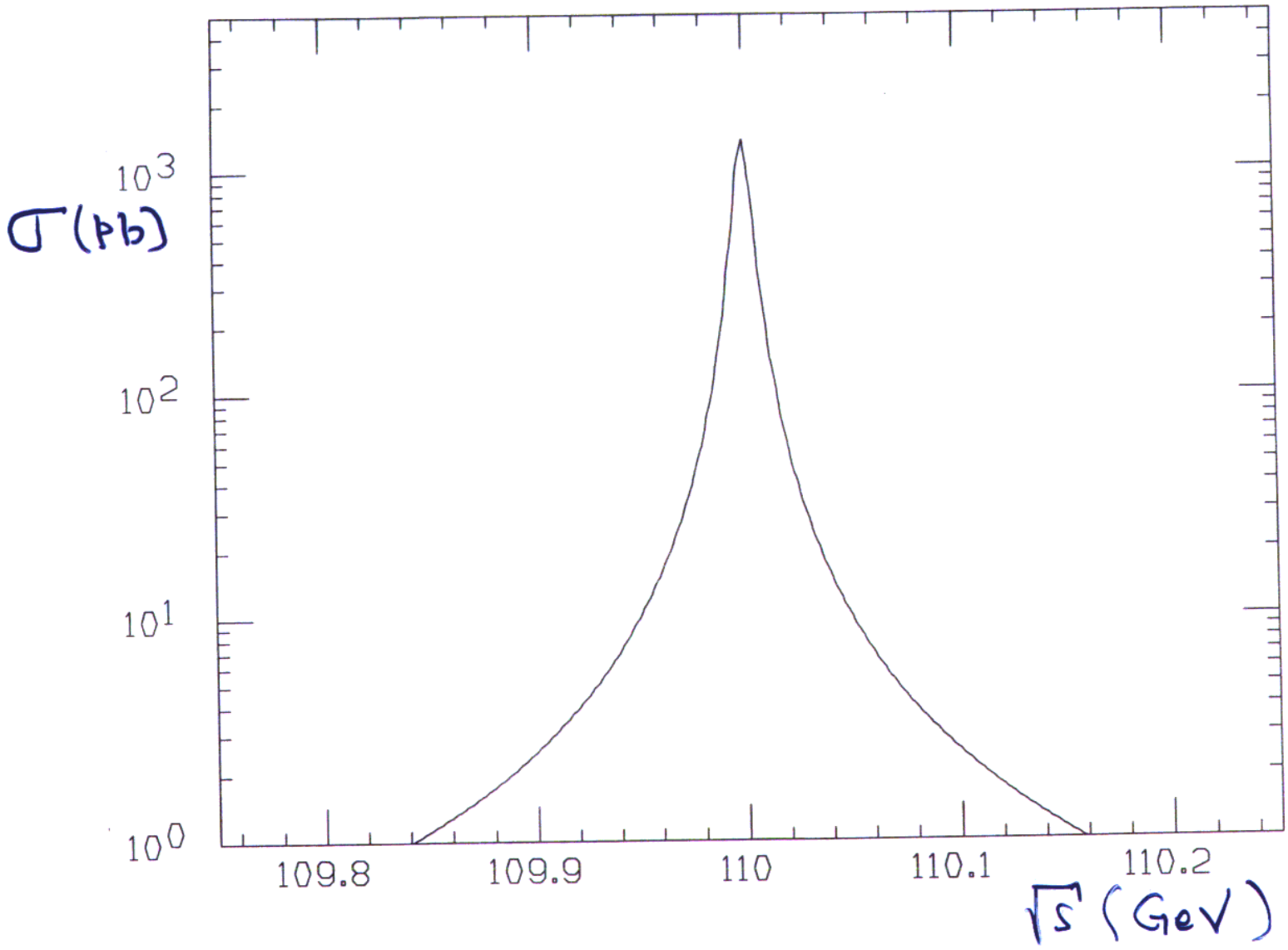
$\Rightarrow \mu^+\mu^-$ Collider will be a remarkable facility


$\mu^+\mu^- \to \rho_T$
$m_\rho = 210$ GeV
$m_{\pi_T} = 110$ GeV
1000 pb
10^6 events/year @ $\mathcal{L} = 10^{32}$
WW/WZ
$W\pi/Z\pi$
σ (pb)
10^0
10^1
10^2
10^3
10^4
206
208
210
212
214
$\sqrt{s}$ (GeV)

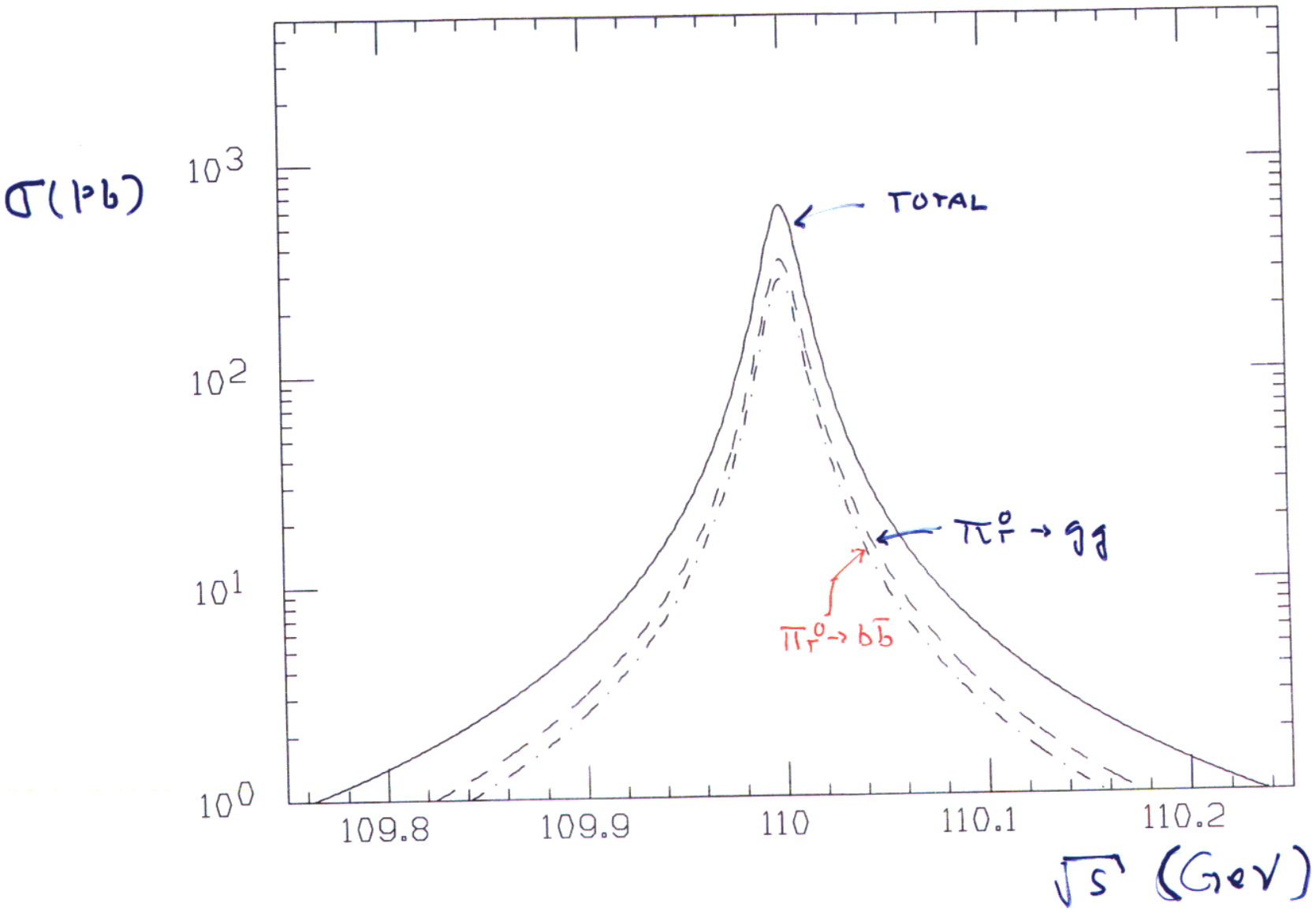

$\mu^+\mu^- \to \rho_T$
$m_\rho = 400\,GeV$
$m_{\pi_T} = 150\,GeV$
10 pb
10^4 events/yr @ $\mathcal{L} = 10^{32}$
σ (pb)
10^2
10^1
10^0
10^{-1}
10^{-2}
360
380
400
420
440
$\sqrt{s}$ (GeV)

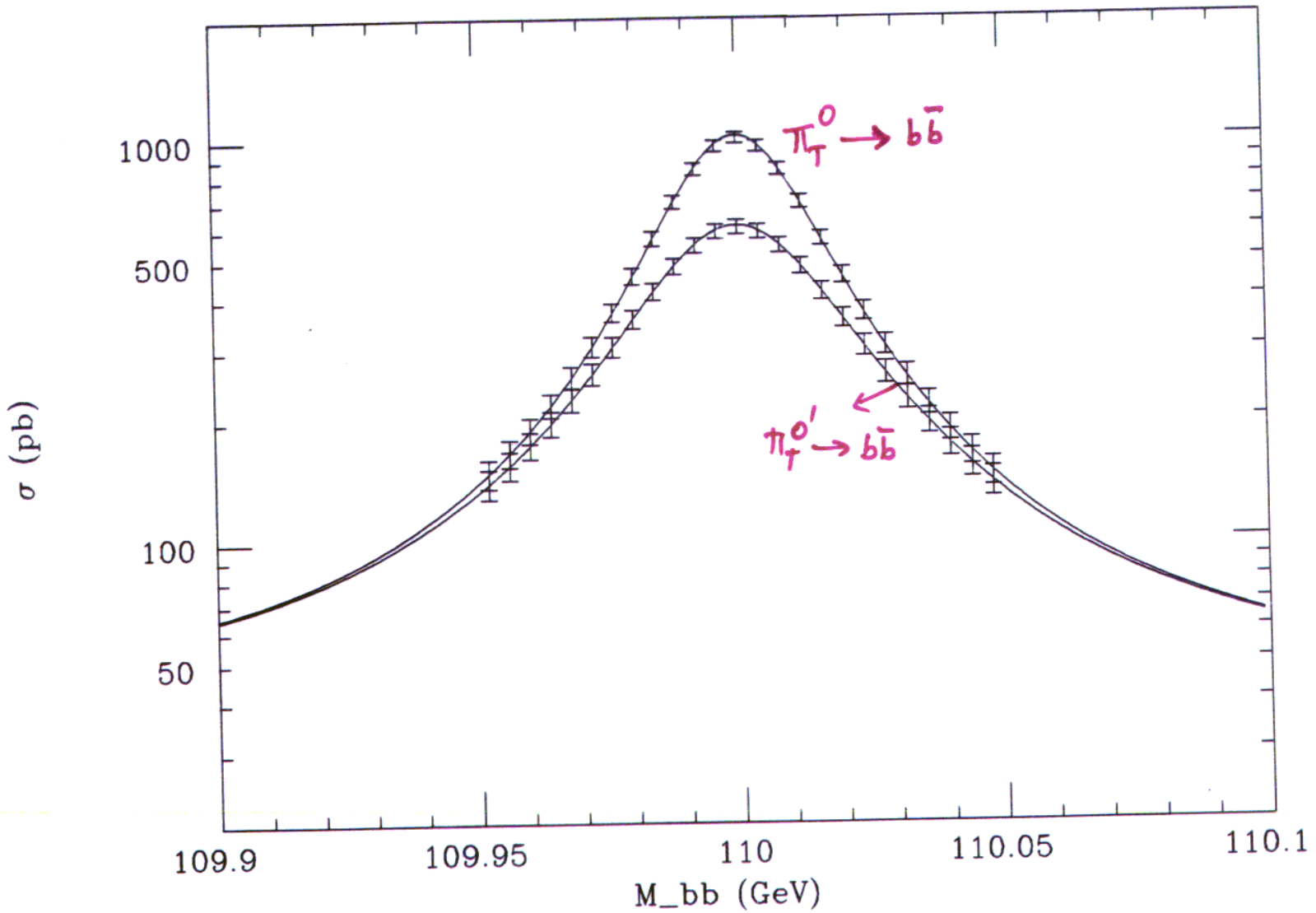

$\mu\mu \to \omega_T$
$m_\omega = 210$ GeV
$m_\pi = 110$ GeV
10^4 pb
$\Rightarrow 10^7$ events/year
@ $\mathcal{L} = 10^{32}$
σ (pb)
10^4
10^3
10^2
10^1
10^0
206
208
210
212
214
216
$\sqrt{s}$ (GeV)

$\mu^+\mu^-$ → isovector π_T^0 → $b\bar{b}$

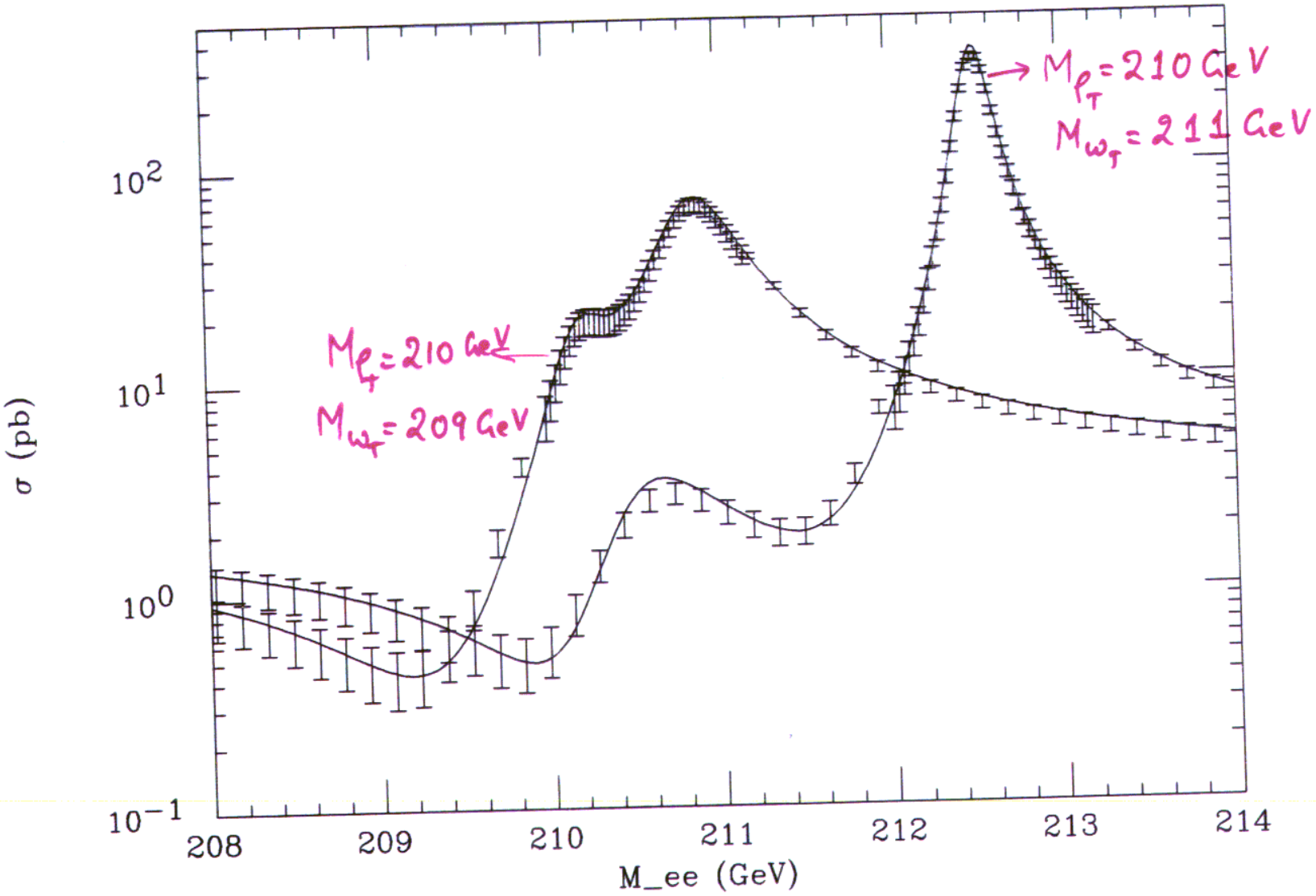


$\mu^+\mu^- \to$ ISOSCALAR $\pi_T^{0\prime} \to b\bar{b}$, gg




1000
500
100
50
σ (pb)
109.9
109.95
110
110.05
110.1
M_bb (GeV)
$\pi_T^0 \to b\bar{b}$
$\pi_T^{0'} \to b\bar{b}$

$\mu^+\mu^- \to \rho_T, \omega_T \to e^+e^-$



A small non-zero isospin splitting between ρ_T and ω_T can produce dramatic interference in $\mu^+\mu^- \to f\bar{f}$

AT THE FMC

- Technicolor low enough in mass to be produced at the FMC will have been discovered at The Tevatron – certainly at the LHC
- So, precision measurements would be the goal
- FMC can be a technipion factory
- Sit on the resonance and study all decays and BR's of the ρ's, ω's and π's
  (all-hadronic modes are hard at the hadron colliders
- Explore the full spectrum of hadrons
- Study (ρ, ω) interference

SUMMARY

- Technicolor is an intuitively attractive and ambitious ansatz for dynamical Electroweak symmetry Breaking.
- Several low energy signatures are accessibl at the Tevatron and LHC.
- Searches are underway at the Tevatron. Rates ~x10 larger at LHC. So, TC signatures should be easily observable
- Muon collider would be a remarkable facility to study technicolor. Spectacular narrow resonances are expected.
- We don't know how nature has chosen to break Electroweak symmetry and flavor symmetry. We should be open-minde